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# AERIAL OBSERVATIONS OF THE SEA SURFACE OFF THE ATLANTIC COAST OF THE UNITED STATES 1/


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## ABSTRACT


Wind direction and speed, wave direction and period, and the position of the landward boundary of the Gulf Stream were measured along a 2600-km coast during three days of an airplane survey. The observations made at about 690 points revealed a close correlation of wind streamlines with isobaric lines of weather maps. Each day three to four wave trains were observed, at least one of which was related to the then prevailing wind. A wind convergence above the landward margin of the Gulf Stream may be due to low pressure produced by warming of the air by the northeasterly flowing water.




1/Contribution No. 1602 of the Woods Hole Oceanographic Institution.

## INTRODUCTION

During recent years many new devices have been developed for study of the ocean, but perhaps none is so exotic as manned satellites, as proposed by the National Aeronautical and Space Administration (Ewing, 1965). Among the many kinds of possible observations are ones based upon visual (or photographic) evaluation of waves, currents, and shoreline features. Supporting information can be provided by infrared and radar measurements of the sea surface. As a step in estimating the research potential of manned satellites, funds provided by the National Aeronautical and Space Administration (contract 22-014-003 to Gifford C. Ewing of Woods Hole Oceanographic Institution) permitted an observational flight along the entire Atlantic coast of the United States aboard the Institution's four-engine (C-54Q) airplane. Observations during the flight also contribute to the knowledge of the effect of wave trains from various directions upon longshore movement of beach sands.

The flight took place during 17 to 21 December 1964; however, icing conditions and poor visibility caused the airplane to be grounded on 18 December and eliminated 21 December for useful work. During the three other days a total distance of 5800 km (Fig. 1-A)

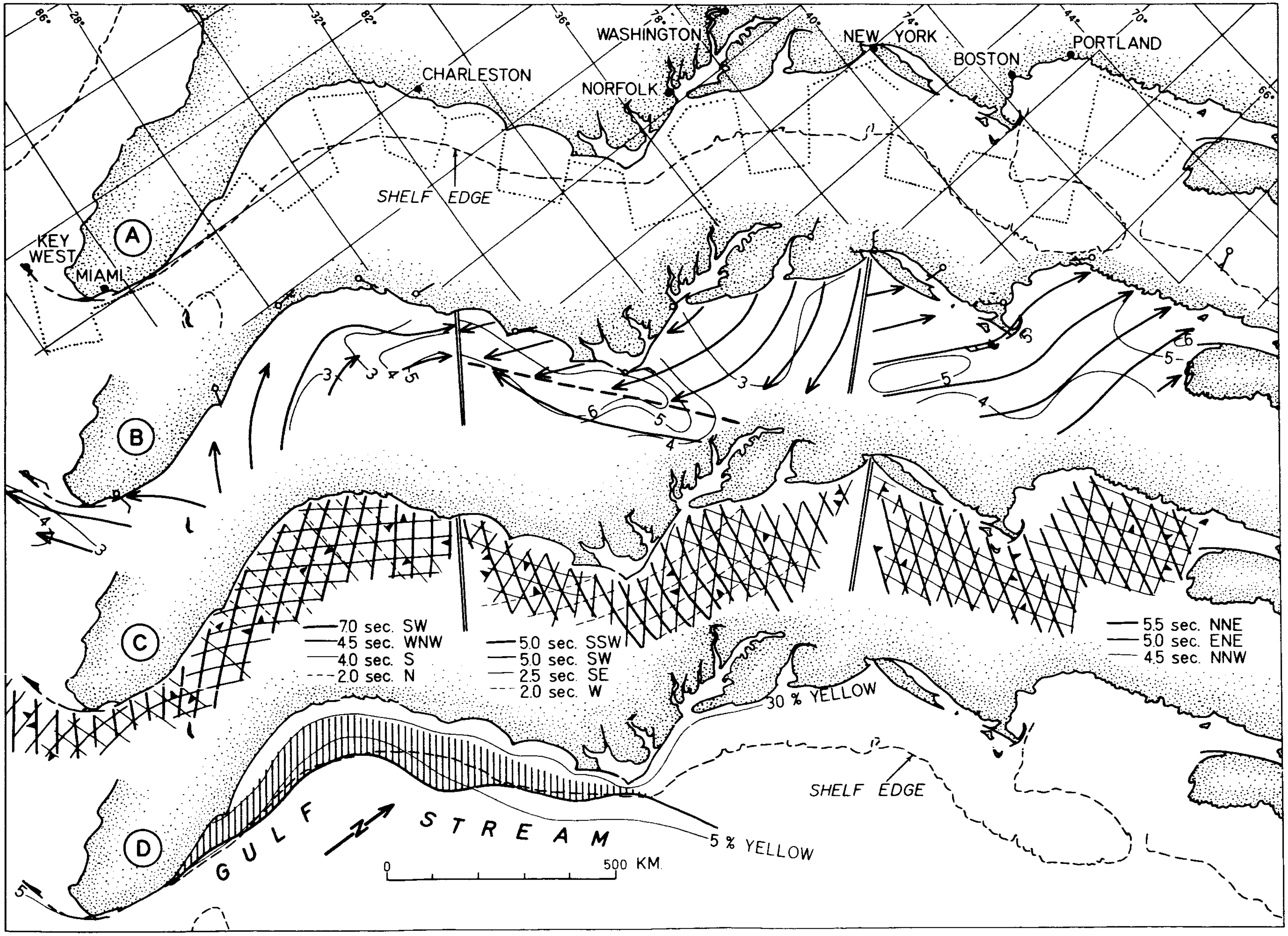
Fig. 1. Summary of observational results off the Atlantic coast of the United States during flights of 17 December (northeast of New York), 19 December (New York to Charleston), and 20 December (south of Charleston).

A. Flight path and positions of observation points at two-minute intervals (about 10 km apart). The broken line denotes the position of the seaward edge of the continental shelf (about 80 meters deep at the south and about 140 meters at the north).

B. Wind streamlines inferred from wind slicks at sea. Numbers indicate Beaufort Wind Force as estimated from the condition of the sea surface. Feathered arrows at shore stations denote observations reported on the Daily Weather Map (National Meteorological Center, 1964) for 0100 Eastern Standard Time.

C. Wave trains and their direction of movement (arrow points) based upon observations of the sea surface. The wave periods are estimates of the time required for crest-to-crest movement of the waves beneath foam patches. Note that one wave train of each day is approximately at right angles to the wind streamlines.

D. Position of the western margin of the Gulf Stream is indicated by the wide line that is bordered by a zone of transition between the Gulf Stream and the coastal water. Water color based upon the Forel scale reveals a transition from blue (less than 5% yellow) at sea to green (more than 30% yellow) near the coast.


KEY WEST
MIAMI
CHARLESTON
WASHINGTON
NORFOLK
NEW YORK
BOSTON
PORTLAND
SHELF EDGE
A
B
C
D
70 sec. SW
4.5 sec. WNW
4.0 sec. S
2.0 sec. N
5.0 sec. SSW
5.0 sec. SW
2.5 sec. SE
2.0 sec. W
5.5 sec. NNE
5.0 sec. ENE
4.5 sec. NNW
30 % YELLOW
5 % YELLOW
SHELF EDGE
GULF STREAM
0
500 KM.

was flown over the ocean between about 0900 and 1600 Eastern Standard Time each day, the hours of best visibility. The flight elevation was 360 meters except during a few hours when a different level was required to avoid clouds.

## WINDS

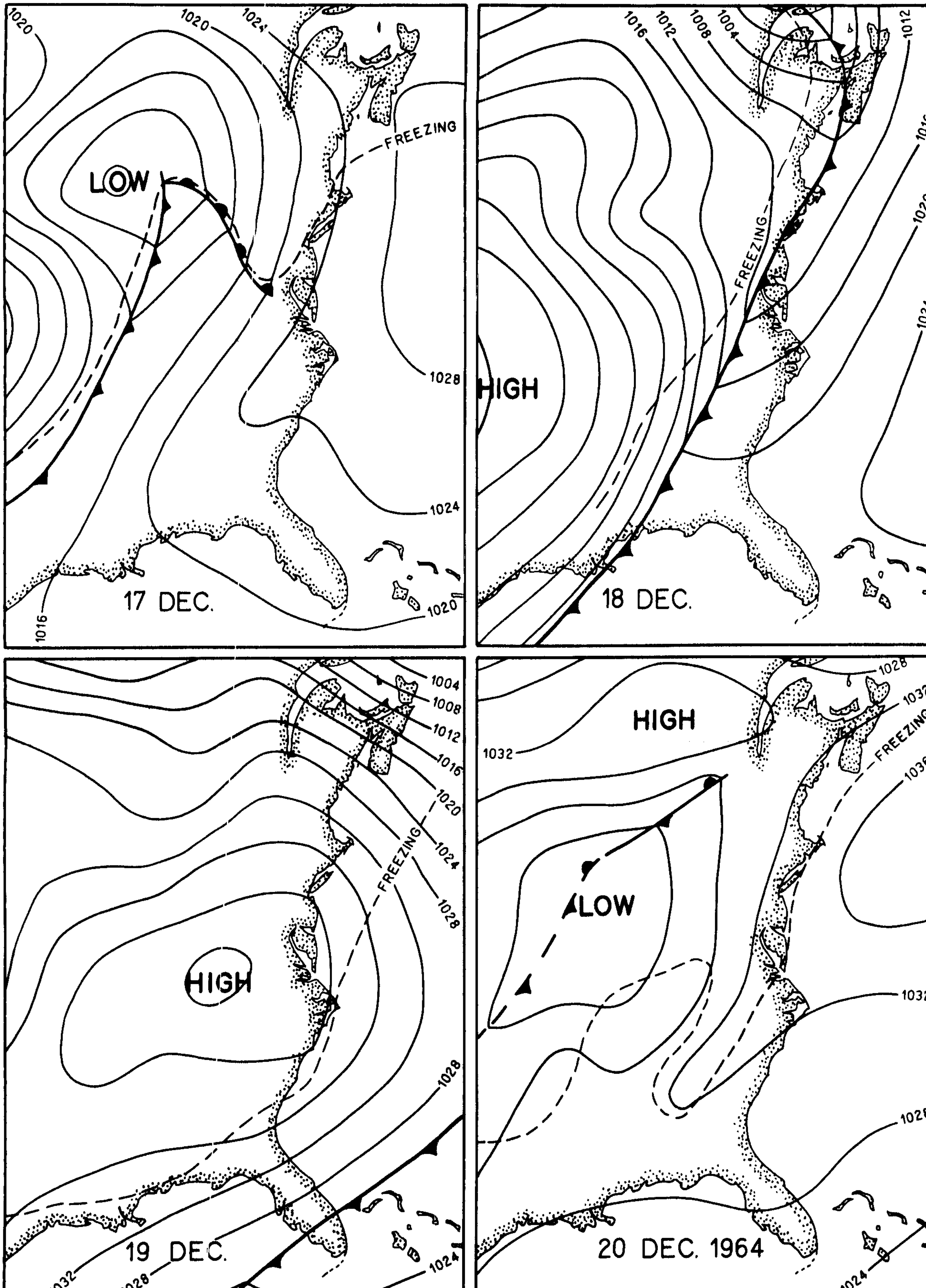
Wind direction was taken as the direction relative to true north of the wind slicks, which form a pattern of nearly parallel strips of smooth water, coupled with the observed direction that whitecaps were blown. As shown by Woodcock (1944), Dietz and LaFond (1950), and Ewing (1950), wind slicks are zones of accumulation of floating debris including oil films. Some of the slicks that were observed during the flight consisted of elongate parallel patches of the free-floating brown gulf weed (Sargassum). The speed of the wind was expressed as Beaufort Wind Force estimated from the character of the sea surface, as defined by Bowditch (1962, p. 1059). Observations of wind direction and speed were made at two-minute intervals during the overwater flight time. Thus, data were derived from about 690 geographic points, far more than can reasonably be obtained for either ships at sea or weather stations on land for a corresponding area of about 600,000 sq. km.

The winds, shown by Figure 1-B, exhibit strikingly different patterns during each of the three days. On 17 December the wind was southwesterly, flowing in a broad curve into the Gulf of Maine with highest speeds near shore and at the entrance of the Bay of Fundy. Data at shore stations closely conformed in direction, according to the Daily Weather Map for 0100 Eastern Standard Time. The same map shows the presence of a low pressure area to the west (Fig. 2) which evidently was responsible for the southwesterly direction of the winds.

The cold front associated with the low pressure area reached the coastal zone on 18 December and produced such unfavorable conditions that the flight was cancelled for that day. By the next day the cold front had moved well out to sea, and a high pressure area bordered the coast on the west. Winds associated with this high should have been approximately northerly, and data from shore stations and aerial observations showed that such winds indeed were present. The aerial observations in addition revealed the presence of a wind convergence over the approximate western margin of the Gulf Stream. In the same vicinity the winds at the sea surface exceeded Force 6, and the area was marked by low clouds, haze, and turbulent air, probably related to the rise of air above the convergence. This convergence is independent of the cold front, which should have passed the area about 30 hours earlier; future observations may indicate that it is a semipermanent feature associated with the edge of the Gulf Stream and caused by heating of the air by the northeastward-flowing warm water, particularly during winter.

Winds of the third day, 20 December, were more complex. Off most of the Florida-Georgia coast the wind

Fig. 2. Isobaric lines (in millibars) for eastern United States during the flights of 17 to 20 December. Data are from Daily Weather Maps of the Weather Bureau (National Meteorological Center, 1964) for the hour 0100 each day.


LOW
FREEZING
1020
1024
1028
1016
17 DEC.
HIGH
FREEZING
1016
1012
1008
1004
1020
1024
18 DEC.
HIGH
FREEZING
1004
1008
1012
1016
1020
1024
1028
1032
19 DEC.
HIGH
LOW
FREEZING
1028
1032
1036
1024
20 DEC. 1964

was southeasterly, in conformity with the presence of a low pressure area to the west (see Figure 2 for 0100 isobaric lines). Near Miami the wind streamlines diverged so that northeasterly winds were present both at sea and at shore stations near the tip of the Florida peninsula. Lowest wind speeds were observed in the vicinity of the divergence, as seems reasonable.

Poor visibility and icing conditions on 21 December were produced by the arrival at the coast of the low pressure area. These conditions required cancellation of the observations north of Florida; the results obtained off southern Florida were generally similar to those of 20 December, but they are not included in Figure 1.

## WAVES

Wave trains were measured at each of the approximately 690 observational stations (Fig. 1-C) using the same visual technique that was developed for similar wave studies off southern California and Hawaii (Emery, 1958, 1963). The only required equipment is a small pelorus fixed on a frame near a window or observation blister of an airplane. The true heading of the airplane reported by the pilot through an intercom was set on the pelorus circle. Each of three bars that are pivoted at the center of the pelorus was kept aligned with a different train of waves. At two-minute intervals the azimuth of each wave train was recorded; less frequent notes about its direction of movement and period were made. The period was based upon the time required for the crest of one wave to be replaced by the crest of the following one beneath a patch of foam or a bit of gulf weed; the method is considered accurate to only about the closest second.

Estimation of the azimuth of a given wave train is rarely possible by viewing the sea surface vertically downward; instead, the waves are best seen by viewing the advancing side at an oblique horizontal angle and at a downward angle of $15^{o}$ to $45^{o}$. A second wave train is best viewed in a different direction, and a third in a still different direction. The various directions of best viewing, coupled with the need to integrate over several tens of seconds, largely eliminates photographic methods of recording for later interpretation.

The results obtained during 17 December (northeast of New York) showed that the longest period waves (about 5.5 seconds) were closely related to the wind streamlines. Two other wave trains moved at approximately $45^{o}$ to the first one. Both were of shorter period, and thus they should not have been produced by distant storms (Munk, 1947), even though one of them moved almost directly landward. Possibly all three wave trains resulted from the same wind.

Four wave trains were observed on 19 December. One of them (5.0 second) moved approximately in the same direction as the streamlines. As on the first day, two other wave trains moved at about $45^{o}$ angles on either side of the first train; one of these, however, was of much shorter period (2.5 seconds). The fourth train, of shortest period (2.0 seconds) moved directly landward, more or less at 90° to the first-mentioned wave train. None of the four trains of waves appears to be related to any of the three trains observed during 17 December, suggesting that the oppositely directed wind streamlines controlled the waves.

Some of the wave trains that were observed during 20 December may be the same as those of 19 December. The longest-period wave (7.0 seconds) had a general southerly movement and perhaps is the continuation of the wind-driven 5.0-second one seen farther north, but now somewhat aged and moving against the wind. Similarly, a 4.0-second wave moving southward may be the aged equivalent of the 2.5-second wave observed on 19 December. A 2.0-second wave, present only off northern Florida and Georgia, may have been developed by a change of wind direction (compare wave patterns with wind streamlines). A 4.5-second wave moving westnorthwest and westsouthwest (at the south) more or less conforms to the existing wind streamlines.

## MISCELLANEOUS OBSERVATIONS

Infrared measurements during the flight showed a gradual decrease in the temperature of the offshore water from about 25.0°C off Miami to about 22.5°C off Norfolk. A gradual to sharp landward decrease began at a boundary line shown at the seaward side of the lined area of Figure 1-D. Near shore the decrease in temperature ended with more uniform but lower temperatures (13°C to 15°C) along the shore between Miami and Norfolk. This transition is inferred to mean that water from the Gulf Stream mixed with that atop the continental shelf. Northeast of Cape Hatteras (about 200 km southsoutheast of Norfolk), where the Gulf Stream veers seaward away from the continental shelf, its landward edge is very sharp as though lateral mixing were less intense over the deep-sea floor.

The Gulf Stream consisted of dark blue water (less than 5% yellow on the Forel scale), in contrast to green (more than 30% yellow) and even yellow to brown water closer to shore. Floating masses of gulf weed were abundant in the Gulf Stream, uncommon in the transitional zone, and not noted in the nearshore water. These measurements of temperature, color, and gulf weed supplemented the low marginal clouds and the convergence of winds in delineating the landward edge of the Gulf Stream.

## SUMMARY AND CONCLUSIONS

The period of the airplane flights was one of perhaps unusually varied weather, with the passage of two low pressure areas and one high pressure area across the coast. The estimates of wind direction, based upon wind slicks and whitecaps, were supported by measurements at most shore weather stations, and they closely followed the pattern to be expected from isobaric maps. In fact, the winds at sea followed the isobars more closely than do winds ashore probably because of the smoother surface of the ocean.

Three to four wave trains were identified and mapped. One appeared to be related to the wind streamlines, lying directly athwart them. Two others, lying on either side of the main wave train, form a diamond-shaped interference pattern that may be due to gusts of the local wind (R.G. Stevens, Woods Hole Oceanographic Institution, personal communication). Of the eleven observed trains (Fig. 2-C), five moved generally parallel to the coast, five moved landward, and one moved seaward. The general impression gained from the wave patterns supports the knowledge of movement of beach sand provided by the curvature of spits, the displacement of river mouths, and the accumulation of beach sand against artificial obstructions. The movement of beach materials is directed mostly toward coastal indentations, no novel conclusion.

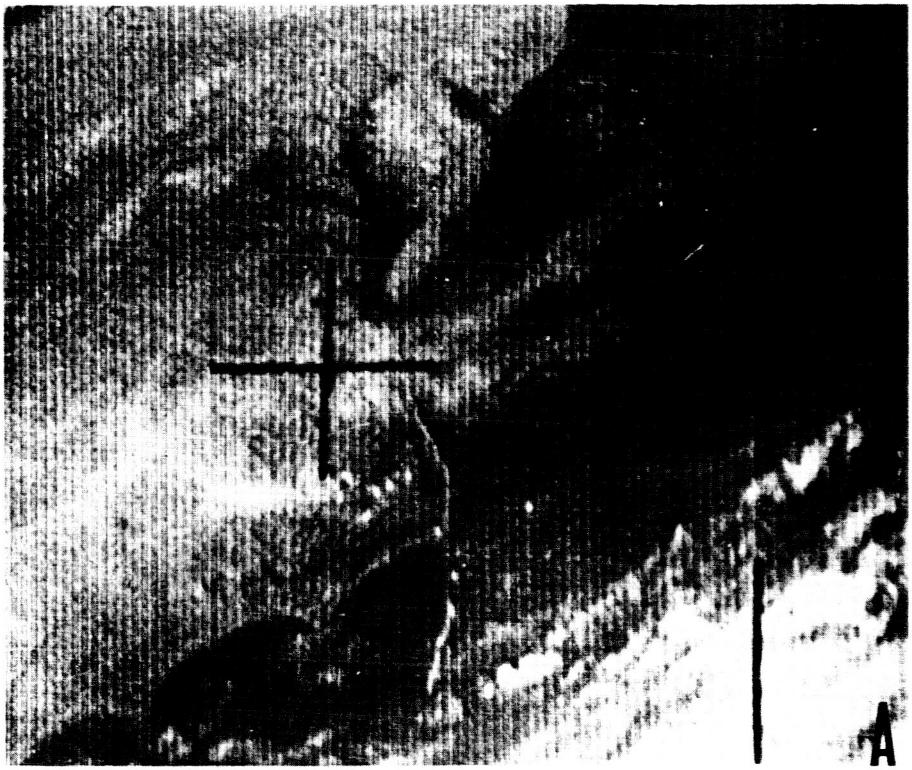
The landward side of the northeasterly-moving Gulf Stream was marked by a wind convergence and low clouds, by an increase in yellowness of the water, and a decrease in abundance of floating gulf weed. The current generally followed the edge of the continental shelf and thus it approached the shore only where the shelf is narrow as at Miami and Cape Hatteras. Meanders of the current, such as those described by Stommel (1958, pp. 72-73), were not detected, but perhaps they are more common over deep water northeast of Cape Hatteras than in the area of the survey where freedom of movement is limited by the edge of the continental shelf.

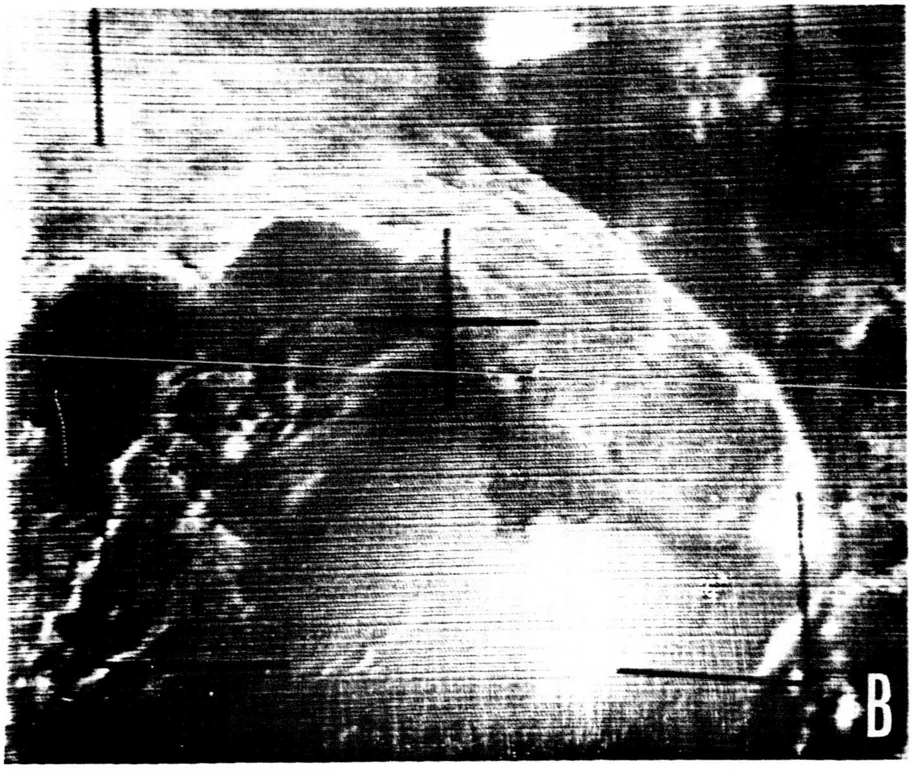
Use of a satellite as a platform probably will restrict direct viewing to such large features as the Gulf Stream. Two TIROS transmissions showing the coast between Cape Hatteras and Key West contain cloud formations that perhaps are related to the edge of the Gulf Stream (Fig. 3). Wave trains probably cannot be mapped from the several hundred kilometer elevation without use of instruments such as telescopic cameras. Probably wind slicks cannot be mapped at all, because they are hardly evident at near-vertical angles of viewing.

Fig. 3. TIROS transmissions that contain linear clouds suggestive of those that were observed during the airplane flight near the landward margin of the Gulf Stream.

A. Cape Hatteras region

B. Florida


A


B

ACKNOWLEDGEMENTS

Appreciation is due Captain William Ewing and Co-pilot Jack Cornell for their skillful piloting and navigation using Loran-A and doppler radar. Assisting in the observing and recording of wind, waves, and miscellaneous data were Jobst Hülsemann (Woods Hole Oceanographic Institution) and A. R. Tagg (U. S. Geological Survey, Woods Hole, Massachusetts). Simultaneous measurements of sea surface temperature by infrared scanner were made by Richard Stone and Thomas F. Azarovitz (Bureau of Sportfisheries, U. S. Fish and Wildlife Service, Sandy Hook, New Jersey); details of their results will be reported separately.

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